

**NASA EPSCoR Preparation Grant  
Final Report**

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## **1. Introduction**

The NASA EPSCoR project in Mississippi involved investigations into three areas of interest to NASA by researchers at the four comprehensive universities in the state. These areas involved:

- Noninvasive Flow Measurement Techniques by Prof. G.D. Huffman, Center for Computational Sciences, School of Engineering Technology, the University of Southern Mississippi
- Spectroscopic Exhaust Plume Measurements of Hydrocarbon Fueled Rocket Engines by Prof. M.J. Plodinec, Diagnostic Instrumentation and Analysis Laboratory, Mississippi State University
- Integration of Remote Sensing and GIS data for Flood Forecasting on the Mississippi Gulf Coast by Prof. G. Easson, Department of Geology and Geological Engineering, The University of Mississippi, and Prof. P. Fitzpatrick, Department of Physics, Jackson State University

Each study supported a need at the Stennis Space Center in Mississippi. The first two addressed needs in rocket testing, and the third, in commercial remote sensing. Students from three of the institutions worked with researchers at Stennis Space Center on the projects.

A summary report of the results of the research in each area is given below.

## **2. Noninvasive Flow Measurement Techniques**

Because of their extreme conditions, flows of cryogenic liquids like oxygen and hydrogen used as rocket propellants cannot be measured using invasive techniques. Rather, noninvasive meters must be used. Transient time Doppler meters, based on the propagation of high frequency sound waves in the fluid, offer many advantages, but still present challenges when used with cryogenic fluids. The flowmeters respond to the average fluid and sonic velocity along a beam path. Since cryogenic fluids are subject to wall heating, a temperature, and thus sonic velocity, profile exists along the pipe. Furthermore, the flowmeter is typically installed a relatively short distance downstream of one or more elbows, creating a three-dimensional flow field. The average values will not accurately represent the mass-averaged fluid velocity. Consequently, the meter must be calibrated for each installation and flow condition. The purpose of the present research was to develop an experimentally verified, theoretical calibration method.

The theoretical calibration method employs two components: a computational fluid dynamics (CFD) program capable of analyzing three-dimensional, heated turbulent flows and an ultrasonic ray tracing program capable of determining ray transient times. This work is unique in that it extends the state-of-the-art to variable temperature flow fields

and uses meter transient times to determine the sonic velocity and, thus, the mass-averaged fluid temperature.

The following tasks were completed under this contract:

- Existing noninvasive flowmeter technology was reviewed.
- The meter type with the most potential for cryogenic fluid measurements was selected.
- Meter limitations and technology requirements for rocket engine testing were determined.
- A suitable CFD program was acquired.
- A three-dimensional, variable sonic-velocity ultrasonic ray trace model was developed.
- The CFD-ray trace model was verified with existing constant temperature data for flows downstream of single and double elbows.
- The model was extended to heated wall flows.

The calculations were performed with the Fluent computer program, using the standard  $k-\epsilon$  turbulence model. The Reynolds number was assumed to be  $10^5$ . The results are calculated in terms of a "meter factor," the ratio of the actual (computed) velocity to the nominal velocity for a uniform, constant temperature flow. In addition to calculating the factors for constant and variable temperature flows downstream of single and double elbows, they were also determined for fully developed flows with wall heating.

### **3. Spectroscopic Exhaust Plume Measurements of Hydrocarbon Fueled Rocket Engines**

A critical element of NASA programs to develop future generation reusable launch vehicles is integrated vehicle health maintenance (IVHM). The primary goals of IVHM are to improve system safety and reduce operational costs by providing continuous status monitors for vehicle systems. Monitoring engine health via optical sensors has long been a standard component of the ground testing performed for space shuttle main engines. This very successful work has focused on the detection of emissions from metallic species in the engine plume using optical spectrometers. These measurements provided excellent engine health monitoring data for the clean plume resulting from hydrogen and oxygen combustion and clearly demonstrated the utility of spectroscopic measurements for engine health monitoring. However, an intense spectral background has prevented extending these efforts to hydrocarbon and solid fueled systems. Thermal emission from

soot and emissions from the vastly more complex combustion products present in such plumes cause this background interference.

The purpose of this EPSCoR project was to evaluate laser technology for extending the capabilities of the engine health monitoring system, primarily for ground-test applications. Initial evaluations of Laser Induced Breakdown Spectroscopy (LIBS) have been carried out in an effort to overcome and reject background plume emissions while allowing detection of metallic species important for engine health monitoring. In LIBS, a pulsed laser beam is focused down to a small spot in the plume. The intense electric field at the focal spot causes a small spark, generating emission from metallic elements. By detecting only the emissions occurring immediately after the spark, background emission interference can be reduced over traditional emission spectroscopy techniques.

Experiments were carried out using a hydrocarbon burner, as well as in a hybrid rocket motor simulator. For both sets of experiments, it was necessary to seed the system with metallic species, Fe, Cr and Ni.

A Q-switched frequency doubled Nd:YAG laser (Continuum Surelite III) that delivers energy of ~300 mJ pulse at a wavelength of 532 nm with repetition rate of 10 Hz and pulse width 3 -5 ns was used to generate a spark in the hydrocarbon flame and the rocket motor simulator plume. The laser beam was reflected at a harmonic separator to remove its fundamental infrared component. The 532-nm beam was then reflected to the probe lens through a dichroic mirror, which reflects 532 nm but transmits other wavelengths. The laser was focused in the flame and in the rocket motor simulator plume using an ultraviolet grade quartz lens of 10-cm focal length to produce a breakdown spark. The same focusing lens was used to collect and collimate the emission from the breakdown plasma. The LIBS signal was transmitted through the dichroic mirror and coupled to a fiber optic bundle with two additional lenses for routing to an Instruments SA Model HR 460 spectrometer equipped with an ICCD detector. The spectral region monitored by the detector was ~30 nm wide with a resolution of ~0.15 nm with the 1200 l/mm grating. The detector worked in the gated mode and was synchronized to the laser Q-switch. To maximize the signal over noise, a gate pulse delay of 30  $\mu$ s and width of 10  $\mu$ s was used in most of the work.

A standard atomic emission spectroscopy system was also used for comparison purposes during the motor simulator tests. Briefly, a lens was used to form 1:1 image of the plume onto an optical fiber. The position of the fiber could be moved in the image to allow for the acquisition of spectra from different region of the plume. The light was collected on one end of a 1-mm diameter optical fiber, which transmits the emission to the input of a spectrometer. The type of fiber selected was optimized for ultraviolet light transmission. Light collected by the fiber was routed to a 0.5 meter Acton spectrometer equipped with a 256 x 1024 pixel CCD detector. A manual shutter mounted at the entrance slit to the spectrometer provided exposure control for the CCD detector. A 2400 line/mm grating was used in the collection of all experimental spectra.

All the emission lines from Fe, Cr and Ni became very clear at a 70  $\mu$ s gate delay due to a

drastic decrease in the background emission from the burner plume. The emission lines from all the elements are very clear. The observation of only Cr and Ni emission line at 40  $\mu$ s gate delay in comparison to iron line seems to be due to the higher concentration of nickel (500 ppm) and the larger transition probability of Cr (10 ppm) than iron (100 ppm). It is clear from this study that in order to observe the line emission from the luminous flame, one has to record the (LIBS) spectrum after optimizing the gate time delay to increase the S/B ratio. The optimum time delay varies from element to element. Recording the spectra in a less luminous zone will also be advantageous in getting a good signal to background ratio.

The LIBS spectrum of the motor simulator plume was recorded with a 316L stainless steel wire of 1.76 mm diameter inserted into the ignition chamber to generate the seed vapor in the plume. The laser was focused approximately 3" from the exit of nozzle. LIBS spectra of the plume indicated the presence of a significant amount of Cr in the plume whereas no iron lines are observed in the spectra at this location. This behavior is likely due to the low concentrations of iron near the exit channel where the plume speed is very high and the possibility that the gate delay time of 30 $\mu$ s may not be sufficient for the observation of iron emission lines. The observation of chromium lines in spite of its lower concentration than iron in stainless steel is likely due to a high transition probability. These observations are similar to those for LIBS spectra recorded from the hydrocarbon flame seeded by the mixture of Fe, Cr and Ni. However, emission lines from the iron became prominent when the spectrum was recorded at a gate time delay of 70  $\mu$ s. This clearly explains the observation of only chromium in the simulator plume. A trace of iron was observed in the LIBS spectrum of the plume, when the spectrum was recorded at higher gate delay, but the signal was very weak. It seems that the high speed of plume is also playing an important role in diluting the concentration of iron in the plume. Finally, a comparatively lower transition probability again may be responsible for the absence of iron line emission in the LIBS spectrum at lower time delays.

The data from these preliminary tests show that the measurements made away from the luminous part of the plume can provide a strong indicator of the presence of trace elements in the rocket motor plume, perhaps an indication of excessive wear in the system.

Emission spectra from the luminous plume of the rocket motor were also recorded for comparison with the LIBS spectra. The emission of the OH molecular band around 315 nm is evident, as are two copper emission lines. These observations are similar to those noted for the LIBS spectrum. However a simple comparison of both the spectra demonstrates the enhanced Cu signal obtained with LIBS vs. standard emission spectroscopy. The signals associated with copper emission are considerably stronger relative to the OH background in the LIBS spectrum.

The temporal evolution of the copper emission was also obtained by plotting the integrated signal of the line emission as a function of time. The copper signal was observed using standard emission spectroscopy for  $\sim$ 9 seconds before becoming indistinguishable from the background intensity level. In contrast, the LIBS signal of

copper from the plume lasts for the duration of motor firing (~20 seconds) with a comparatively lower intensity of signal later in the firing.

In summary, this study of aerosols and metal-seeded plumes indicates that the LIBS signal is lowest in the luminous flame region, but still exceeds that of standard emission spectroscopy. The temporal evolution of the LIBS emission from trace elements (Fe, Cr and Ni) in the flame indicates that the signal to background ratio improves at comparatively longer gate delay times. This is due to the fast decay of background plasma emission from the spark relative to the line emission from the trace elements present in the plume. Some elements such as iron are only weakly observable at lower gate delays even at significant concentrations in the flame. The gas flow rate of the sample also affects the LIBS signal significantly. Normally, LIBS signals increase with an increase in the air flow until very high flow rates, where the signal decreases due to dilution.

The LIBS spectra of the rocket engine simulator plume seeded with stainless steel and copper indicates that the signal is stronger when the LIBS spark is formed out of the luminous zone away from the exit nozzle. Better mixing of the exhaust gas and seeded elements was noted away from the exit nozzle. Strong background emission results in a small signal to background ratio in the flame itself. Two techniques were employed for seeding the elements in the simulator plume. Of these, placing the metallic wire inside the ignition chamber was found to be the best. A better solution with improved mixing and symmetrical injection of seeded elements in the plume would likely be to inject an aerosol of the elements into the ignition chamber.

For standard emission spectroscopy, strong background emission from the plume limits accurate metals measurement at trace levels. A simple comparison indicates that the LIBS technique has several advantages as compared with standard emission methods. In LIBS, a high energy, pulsed laser beam is used to produce atomic emission at the focal volume providing a time and spatially resolved measurement. Gated detection with an intensified CCD detector also discriminates against continuous background emission, which improves detection limits for the metallic species. Comparison of the spectra obtained from LIBS and emission shows that LIBS spectra have higher signal-to-noise and signal-to-background ratio for the metallic emissions.

These measurements in the plume of a hybrid rocket motor simulator suggest that LIBS may have the capability to be an engine health monitor for detecting trace metals originating from motor wear. The experiments described here indicate that the sensitivity of the technique is strongly dependent upon proper optimization of the system operation, particularly with regard to the timing of data acquisition relative to the laser spark. To develop LIBS as a rocket motor health monitor, future work must include the investigation of methods for quantitative metal seeding, optimization of the experimental setup for reducing spectral interference, and optimizing the LIBS sensitivity for trace element measurement. Efforts at DIAL will continue to investigate this technique as a health monitor for ground test or perhaps eventual flight applications.

#### **4. Integration of Remote Sensing and GIS data for Flood Forecasting on the Mississippi Gulf Coast**

The goals of this project were to:

- integrate the predicted precipitation data from Next Generation Radar (NEXRAD) with an overland flow model to develop a Geographic Information System (GIS)-based tool that could be used for both planning and flood forecasting for small municipalities, and
- develop methodologies to use data derived from remote sensing to obtain the parameters needed by overland flow models and to incorporate these parameters into the GIS-based model.

This was a cooperative project between The University of Mississippi and Jackson State University. Overland flow models are commonly used tools to model flow in a basin and determine the amount of water flowing past a selected point. Engineers and city planners have used these tools to assess the impact of changes in basin geometry and conditions. Many of these models were developed by agencies of the federal government, such as the US Army Corps of Engineers.

These models require a knowledge of the conditions in the basin of interest, including land cover, slope, and soil type. Determination of these input parameters is key to developing accurate flow models. The use of remote sensing data will enable the users of these models to have the most current parameters. The models use these conditions with an estimated precipitation to predict the amount of water infiltration and the amount of water that flows overland and accumulates in streams and drainage channels. The ability to input actual precipitation data into the model has been a limiting factor in the use of these types of models as a prediction tool.

This project investigated the different types of overland flow models available in the market place, the majority of which were developed by the US Army Corps of Engineers. Many of these models have been customized to facilitate their operation in a GIS environment. The project selected the Hydrologic Modeling System (HMS) that has been incorporated into an ArcView-based system. The graduate students involved in this project selected this system after a thorough evaluation of the numerous systems available.

The extraction of the parameters needed for overland flow modeling from high resolution remote sensing proved to be more problematic than expected. High resolution imagery, one-meter cell size, is more difficult to classify accurately than more coarse resolution imagery. The imagery used had approximately ten percent of the study area covered by shadows that were cast by trees and buildings. Therefore, the needed parameters could not be determined for ten percent of the study area. An additional graduate student

research project was designed to develop a methodology to reclassify these shadows into the proper land cover. This research will be finished in September, 2002 and the preliminary results were presented at the annual meeting of the American Society of Photogrammetry and Remote Sensing (ASPRS) in Washington, DC in May, 2002.

In addition to the problems with shadows in high resolution imagery, the considerably lower resolution data from the NEXRAD system presented problems in the system development. The NEXRAD data provided the only viable method of obtaining the precipitation data and routines were developed that re-sampled the data and converted it to a GIS compatible format. These routines were developed and tested using archival data from the National Weather Service.

The final step of the development of a complete system that can accept NEXRAD data, obtain parameter data from remotely sensed imagery and predict potential flood is being completed as part of a Doctoral research project funded by the University of Mississippi Geoinformatics Center (UMGC). This project is scheduled for completion in May 2004.